DIRECTIONAL DETECTION OF DARK MATTER

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Directional detection of galactic Dark Matter is a promising search strategy for discriminating genuine WIMP events from background ones. However, to take full advantage of this powerful detection method, one need to be able to extract information from an observed recoil map to identify a WIMP signal. We present a comprehensive formalism, using a map-based likelihood method allowing to recover the main incoming direction of the signal, thus proving its galactic origin, and the corresponding significance. Constraints are then deduced in the (σ_n, m_χ) plane.

1 Introduction

Taking advantage of the astrophysical framework, directional detection of Dark Matter is an interesting strategy in order to distinguish WIMP events from background ones. Indeed, like most spiral galaxies, the Milky Way is supposed to be immersed in a halo of WIMPs which outweighs the luminous component by at least an order of magnitude. As the Solar System rotates around the galactic center through this Dark Matter halo, WIMPs should mainly come from the direction to which points the Sun velocity vector and which happens to be roughly in the direction of the Cygnus constellation. Then, a directional WIMP flux is expected to enter any terrestrial detectors (see fig.1 left) infering a directional WIMP induced recoil distribution which should be pointing toward the Cygnus Constellation, *i.e.* in the $(\ell_\odot = 90^\circ, b_\odot = 0^\circ)$ direction (see fig.1 middle). The latter corresponds to the expected WIMP signal probed by directional detectors and as it is shown on the fig.1 (middle), a strong anisotropy is expected [1] while the background should be isotropic.

Several project of directional detectors are being developed [2] and in this paper, we present a map-based likelihood analysis [3] in order to extract from an observed recoil map the main incoming direction of the events and its significance. This way, the galactic origin of the signal, thus the identification of a genuine WIMP signal, can be proved by showing its correlation with the direction of the solar motion. This blind analysis is intended to be applied to directional data of any detector and as an example we will apply this method to a realistic simulated data.

2 Map-based likelihood analysis

2.1 A realistic simulated measurement

Right panel of figure 1 presents a typical recoil distribution observed by a directional detector : 100 WIMP-induced events and 100 background events generated isotropically. These events

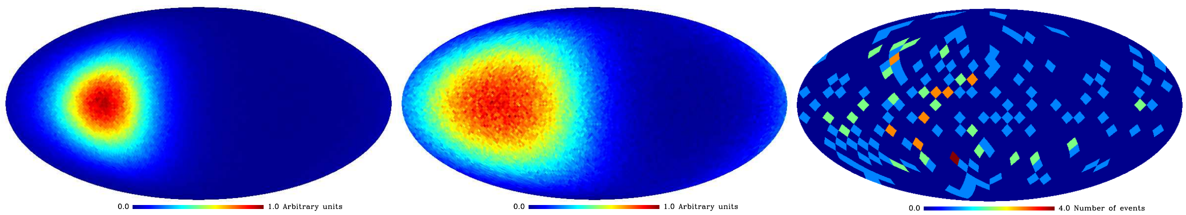

Figure 1: From left to right : WIMP flux in the case of an isothermal spherical halo, WIMP-induced recoil distribution and a typical simulated measurement : 100 WIMP-induced recoils and 100 background events with a low angular resolution. Recoils maps are produced for a Fluorine target, a 100 GeV.c^{-2} WIMP and considering recoil energies in the range 5 keV $\leq E_R \leq$ 50 keV. Maps are Mollweide equal area projections.

are meant to be after data rejection based e.g. on track length and energy selection[4]. For an elastic axial cross-section on nucleon $\sigma_{\rm n} = 1.5 \times 10^{-3}$ pb and a 100 GeV.c^{-2} WIMP mass, this corresponds to an exposure of $\sim 7 \times 10^3$ kg.day in ^{3}He and $\sim 1.6 \times 10^3$ kg.day in CF_4, on their equivalent energy ranges as discussed in [3]. Low resolution maps are used in this case ($N_{\rm pixels} = 768$) which is sufficient for the low angular resolution, $\sim 15°$ (FWHM), expected for this type of detector and justified for instance by the straggling of the recoiling nucleus[4]. 3D read-out and sense recognition are considered.

2.2 Likelihood definition

At first sight, it seems difficult to conclude from the recoil map of fig. 1 (right) that it does contain a fraction of WIMP events pointing towards the direction of the solar motion. A likelihood analysis is developed in order to retrieve from a recoil map : the main direction of the incoming events in galactic coordinates (ℓ, b) and the number of WIMP events contained in the map. The likelihood value is estimated using a binned map of the overall sky with Poissonian statistics, as follows :

$$\mathscr{L}(m_\chi, \lambda, \ell, b) = \prod_{i=1}^{N_{\rm pixels}} P(\lambda S_i(m_\chi; \ell, b) + (1-\lambda) B_i | M_i) \tag{1}$$

where B is the background spatial distribution taken as isotropic, S is the WIMP-induced recoil distribution and M is a typical measurement. This is a four parameter likelihood analysis with m_χ, $\lambda = S/(B+S)$ the WIMP fraction (related to the background rejection power of the detector) and the angles (ℓ, b) corresponding to the coordinates of the maximum of the expected WIMP events angular distribution. Hence, $S(m_\chi; \ell, b)$ corresponds to a rotation of the $S(m_\chi)$ distribution by the angles ($\ell' = \ell - \ell_\odot$, $b' = b - b_\odot$).

A scan of the four parameters with flat priors, allows to evaluate the likelihood between the measurement (fig. 1 right) and the theoretical distribution made of a superposition of an isotropic background and a pure WIMP signal (fig. 1 middle). By scanning on ℓ and b values, we ensure that there is no prior on the direction of the center of the WIMP-induced recoil distribution. In order to respect the spherical topology, a careful rotation of the S distribution on the whole sphere must be done as follows. Given $\overrightarrow{V}_i$ the vector pointing on a bin S_i, the following rotation is considered :

$$\overrightarrow{V}'_i = R_{\vec{u}}(b') R_{\hat{z}}(\ell') \overrightarrow{V}_i$$

with $\vec{u} = R_{\hat{z}}(\ell')\ \hat{x} = u_x\ \hat{x} + u_y\ \hat{y}$ and $R_{\vec{u}}(b')$ is the Rodrigues rotation matrix around an arbitrary vector $\vec{u}$.

The events contained in the observed recoil map can be either a WIMP-induced recoil or a background event. A realistic recoil map from upcoming directional detectors can not be

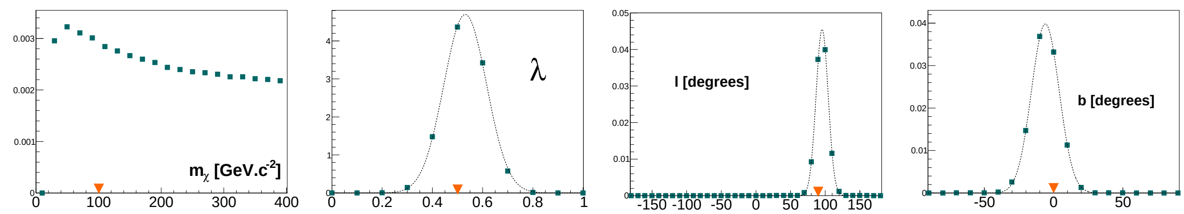

Figure 2: From left to right : Marginalised probability density functions of the following parameters: m_χ, λ, ℓ and b after the likelihood analysis of the simulated recoil map of fig. 1 right.

background free. With this method, both components (background and signal) are taken into account and no assumption on the origin of each event is needed. Indeed, the observed map is considered as a superposition of the background and WIMP signal distribution, and the likelihood method allows to recover λ, the signal to noise ratio. The advantage is twofold :

- Firstly, background-induced bias is avoided. This would not be the case with a method trying to evaluate a likelihood on a map containing a fairly large number of background events considering only a pure WIMP reference distribution.
- Secondly, the value of λ allows to access the number of genuine WIMP events and consequently the scaterring cross-section as presented in sec. 2.4.

It is worth noticing that the likelihood is performed on the whole angular distribution in order to maximize the information contained in an observed recoil map, to be sensitive to the Dark Matter halo shape and to enhance the constraint on the four parameters.

2.3 Results from a realistic recoil map

The four parameter likelihood analysis has been computed on the simulated map (fig. 1 right) and the marginalised distributions plots of the four parameters m_χ, λ, ℓ, b are presented in figure (2). The conclusion of the analysis is threefold:

- Firstly, as the ℓ and b parameters are well constrained, the first result of this map-based likelihood method is that the main recoil direction is recovered and it is pointing towards $(\ell = 95^\circ \pm 10^\circ, b = -6^\circ \pm 10^\circ)$ at 68 % CL, corresponding to a non-ambiguous detection of particles from the galactic halo. This is indeed the discovery proof of this detection strategy.
- Secondly, the method allows to constrain the λ parameters, the WIMP fraction, and then to derive the number of WIMP events contained in the observed recoil map. Indeed, we can estimate the number of WIMP events as $N_{\rm wimp} = \lambda \times N_{tot}$ where $N_{tot} = S+B$ follows a Poissonian statistic, and $\Delta N_{\rm wimp}$ is given by $\Delta N_{\rm wimp} \approx \Delta\lambda \times N_{tot}$. Hence for this simulated recoil map, the reconstructed number of WIMP events is $N_{\rm wimp} = 106 \pm 17$ (68%CL).
- Thirdly, we can notice that the WIMP mass is not recovered, there is only a lower limit: $m_\chi > 10$ GeV.c^{-2}. In fact, m_χ is set as a free parameter in order to show that the analysis is particle physics model independent.

As a conclusion of this analysis, the combination of the two main previous results given by the analysis, which are that the recoil map contains a signal pointing toward the Cygnus constellation within 10° with $N_{\rm wimp} = 106 \pm 17$ (68%CL), leads to a high significance detection of galactic Dark Matter.

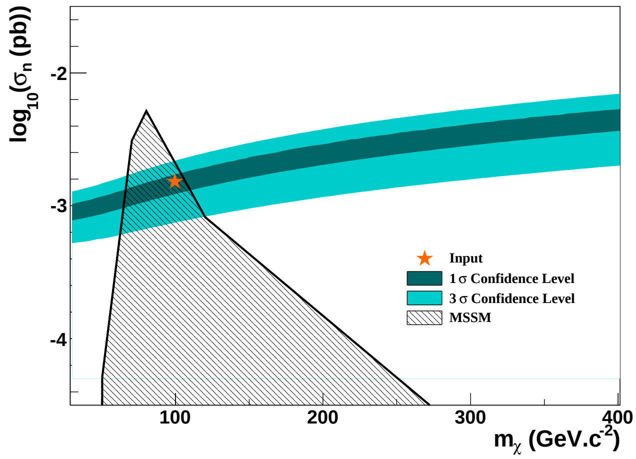

Figure 3: Allowed regions obtained with the example map shown on figure 1. Results are presented in the plane : WIMP cross-section on nucleon ($\sigma_{\rm n}$) as a function of WIMP mass (GeV.c^{-2}), with 1σ and 3σ CL contours. MSSM refers to generic SUSY models and the input value for the simulation is shown with a star.

2.4 Constraining the elastic scattering cross-section

A constraint in the (σ_n, m_χ) plane is then deduced from the marginalised $\mathscr{L}(\lambda)$ distribution evaluated for each WIMP mass above 10 GeV.c^{-2}. Using the standard expression of the event rate with a form factor $F^2(E_R)$ taken equal to one and the local halo density $\rho_0 = 0.3$ GeV.c^{-2}.cm^{-3}, the 1σ and 3σ CL contours are calculated. Figure 3 presents the discovery region deduced from the analysis of the simulated recoil map. It should be highlighted that these contours represent the allowed regions, as directional detection aims at identifying WIMP signal rather than rejecting the background. For reference, generic SUSY models [5] are also shown as well as the input value for the simulation (orange star). Such a result could be obtained, with a background rate of ~ 0.07 kg^{-1}day^{-1} and a 10 kg CF_4 detector during ~ 5 months, noticing that the detector should allow 3D track reconstruction, with sense recognition down to 5 keV.

3 Conclusion

We have presented a statistical analysis tool to extract information from a data sample of a directional detector in order to identify a galactic WIMP signal. As a proof of principle, it has been tested within the framework of an isothermal spherical halo model. We have shown the feasibility to extract from an observed map the main incoming direction of the signal and its significance, thus proving its galactic origin. Systematical studies have been done [3] in order to show that this analysis tool gives satisfactory results on a large range of exposure and background contamination.

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